May 2002 • NREL/CP-500-32511

Conference Paper

Battery Voltage Stability Effects on Small Wind Turbine Energy Capture

Preprint

D. Corbus, C. Newcomb, E.I. Baring-Gould, and S. Friedly

To be presented at the American Wind Energy Association (AWEA) WINDPOWER 2002 Conference Portland, Oregon June 2-5, 2002

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Battery Voltage Stability Effects on Small Wind Turbine Energy Capture

David Corbus, Senior Mechanical Engineer
Charles Newcomb, Staff Mechanical Engineer
E. Ian Baring-Gould, Senior Mechanical Engineer
Seth Friedly, Graduate Research Assistant
National Renewable Energy Laboratory
1617 Cole Blvd
Golden, CO 80401-3393
USA
303-384-6966

Abstract

Previous papers on small wind turbines have shown that the ratio of battery capacity to wind capacity (known as battery-wind capacity ratio) for small wind systems with battery storage has an important effect on wind turbine energy output. Data analysis from pilot project performance monitoring has revealed shortcomings in wind turbine energy output up to 75% of expected due to the effect of a "weak" battery grid. This paper presents an analysis of empirical test results of small wind battery systems, showing the relationships among wind turbine charging rate, battery capacity, battery internal resistance, and the change in battery voltage. By understanding these relationships, small wind systems can be designed so as to minimize "dumped" or unused energy from small wind turbines.

Introduction

The ratio of battery to wind capacity (battery/wind capacity ratio) for small wind systems with battery storage has an important effect on wind turbine energy output. Previous papers (Baring-Gould et al., 2001) have shown shortcomings in wind turbine energy output up to 75% of expected due to the effect of a "weak" battery grid. This battery grid is characterized by voltage rise on the battery bank, primarily due to a low battery/wind capacity ratio. It is also affected by battery type, configuration, and age, as well as the output characteristics of the charge controller for the small wind turbine.

This paper presents an analysis of empirical test results of small wind battery systems, showing the relationships among wind turbine charging rate, battery capacity, and the change in battery voltage. By understanding these relationships, small wind systems can be designed so as to minimize "dumped" or unused energy from small wind turbines.

The small wind battery charging tests were conducted in the Hybrid Power Test Bed (HPTB) at the National Wind Technology Center (NWTC) in Boulder, Colorado. The system configuration included both the AOC 15/50 wind turbine and a 65-kW induction generator wind turbine simulator as a charging source, a TRACE 100-kW inverter, and a 750 -kW-hr flooded lead-acid Decca battery bank. The tests quantify the steady-state voltage rise on the battery bank. Data sets are analyzed in terms of charging current, change in voltage, and battery capacity for a given time step. Battery temperature is kept constant during the tests. Test results are analyzed to show the effect of the variables mentioned on the dumped wind turbine energy.

Losses Due to “Weak” DC Bus Battery Grid

Figure 1 shows a configuration for a typical DC-bus-based small wind system. These systems may include a photovoltaics (PV) system or a backup diesel generator, but they will always include a wind turbine and a wind turbine charge controller and batteries. The wind turbine charge controller limits the current to the batteries when the batteries have reached a full state of charge (SOC), as indicated by the high voltage set point for the charge controller. Batteries that have reached a high SOC must not be overcharged, or they could be damaged.

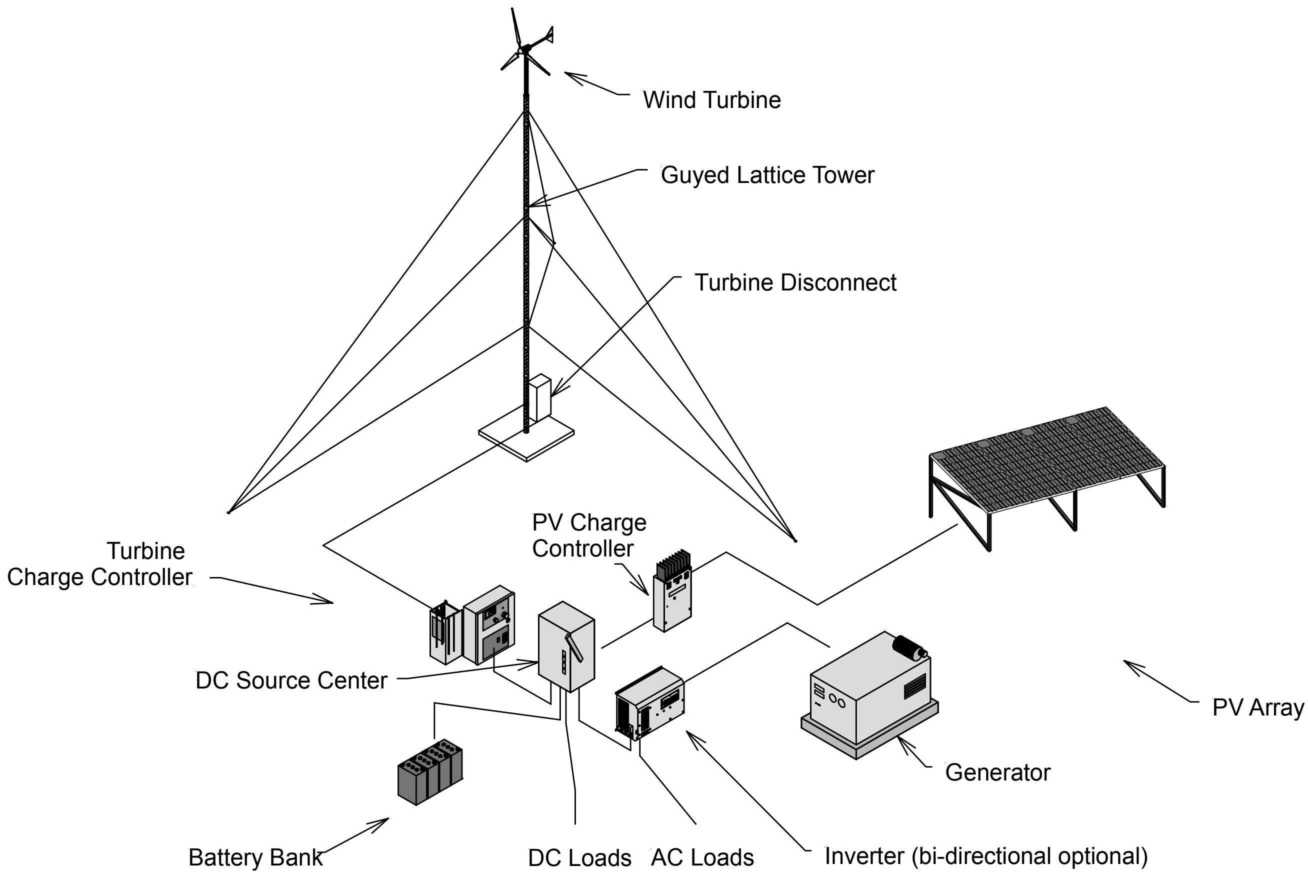

Figure 1. Typical DC-Bus Hybrid Power System

For most of the small wind battery charging systems in the field today, the size of the battery bank limits the amount of power from the wind turbine when the wind turbine is running close to rated power. In many cases, this power is limited well below rated power of the wind turbine. These shortfalls are usually not accounted for in annual energy estimates for these systems. This energy shortfall occurs because the charge controller limits the current to the batteries when the high voltage set point is reached, even though the batteries are not at a 100% SOC (in many cases they are as low as 60% or even less). The high voltage set point is reached prematurely because the voltage rises on the DC bus when the battery/wind capacity ratio is low. This interaction is explained later in this paper, but first a discussion of battery/wind capacity ratios is warranted.

Battery/Wind Capacity Ratio

The battery/wind capacity ratio is an important design parameter that can be used to characterize the amount of storage needed in a small wind battery charging system. It is defined as:

$$\frac{Battery\_Capacity(Ah)}{Wtg\_Current(A)_{@rated\_power}}$$

It can also be defined in kWs and kW-hrs, but the units must be consistent. It is the hours required to fully charge (at the 8-hr rate) initially empty batteries at rated wind power. A smaller battery bank will result in higher DC bus voltage fluctuations for the same turbine under the same charge conditions and hence less power output.

A survey was taken of 25 systems that represented a good cross section of small wind charging systems, as well as one 50-kW PV system and four wind/PV hybrid systems that had some PV capacity. The systems were mostly from international projects; one Field Verification Program site was included. The wind turbines for the systems ranged in size from 400 watts to 50 kWs. Figure 2 shows a histogram of the survey results showing the number of systems that fall within the different battery/wind capacity ratios. The location of the systems is shown in the upper right corner along with the size of the wind turbine in kWs.

The results of the histogram show that most systems fall in a battery/wind capacity ratio of about 7, with 88% of the systems having a battery/wind capacity factor of between 3 and 10. The three systems at 15 and above were all very small wind systems, but there were also many small wind systems within the 3-10 range.

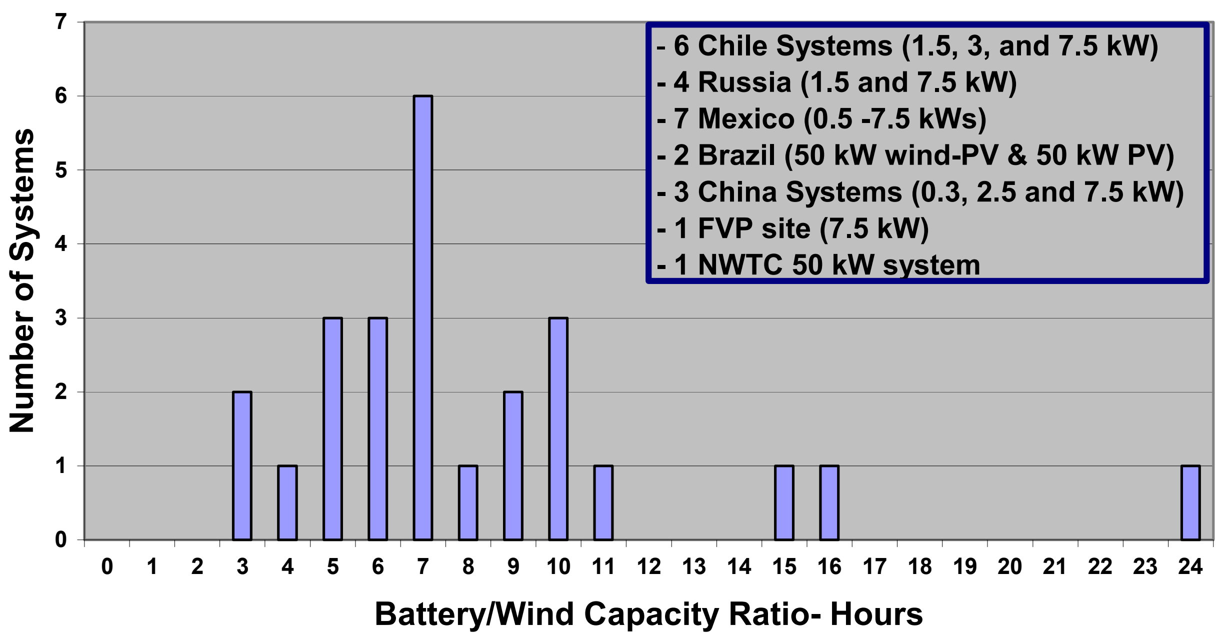

Figure 2. Survey of 25 Representative Small Wind Battery Systems
Small Wind Turbine Battery Charging

Batteries have an important effect on small wind turbine energy output. The battery/wind capacity ratio affects the charging process. Other factors affecting the charging process include the battery bank age, configuration, cell type (e.g., flooded versus sealed), charging history, and temperature. The relationship between charge rate and battery capacity is important. Figure 3 shows the amp-hour capacity versus charge rate for the batteries used for testing at the NWTC (described in the next section), based on data from the manufacturer. Note that the change in battery capacity in Figure 3 is greatest at lower charge times (i.e., higher charge rates), which is where most wind systems designed with battery/wind capacity ratios of 3-10 operate most.

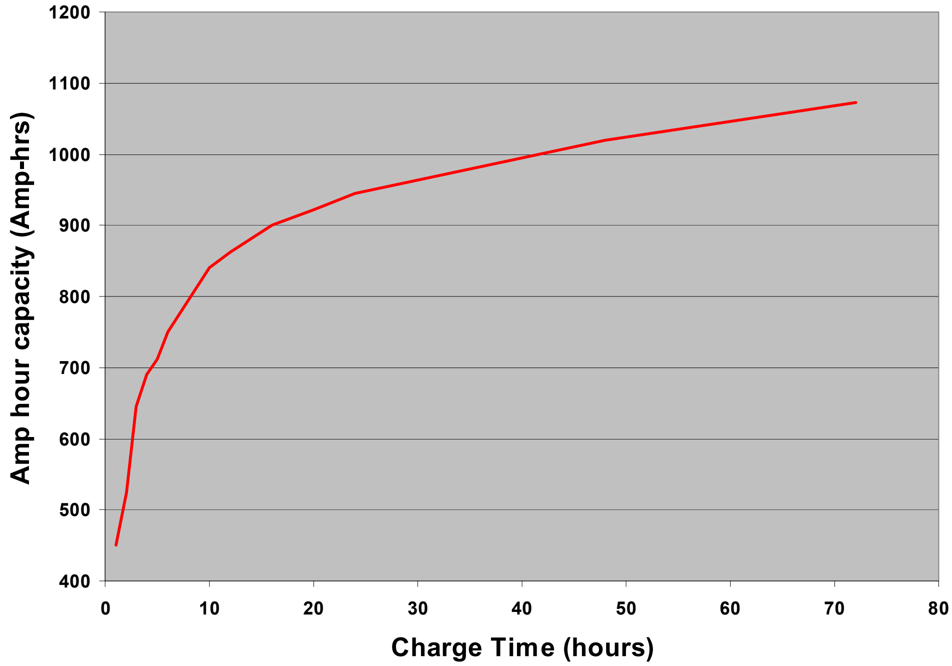

Figure 3. Amp-Hour Capacity Versus Charge Time

Testing at the Hybrid Power Test Bed

Battery testing at the NWTC's HPTB was conducted to better characterize the relationship between battery bank voltage and charge rate for flooded lead-acid batteries. The test results could then be compared to the battery/wind capacity factors from the survey presented in the previous section to help understand why small wind system annual energy production was below predicted. It was originally thought that this test data would be available from previous battery tests reported in the literature, but a thorough literature search revealed no reliable data of this type for flooded lead-acid batteries.

The HPTB is a user facility designed for testing small wind and hybrid systems. The battery testing was conducted using the following HPTB equipment: A TRACE 100-kW inverter configured to operate with an induction wind turbine generator, a 100-kW wind turbine simulator (DC variable-speed drive powering a 100-kW induction generator), a 100-kW village load, a 100-kW dump load, an 85-kW Onan diesel genset, and a 750-amp-hour Decca battery bank. The data acquisition system was a Labview-based system, the sample rate was 2 seconds, and the averaging time 2 minutes.

The battery bank comprised 114 new Deka D125 2-volt cells in series at a nominal voltage of 228 volts and 750 amp-hours (at a 6-hour rate). Batteries were charged at a constant current with the HPTB wind source simulator and Trace 100-kW inverter, and a finish charge was given after every charge test. Batteries were discharged at a 6-hour rate. The SOC for the battery bank was determined by amp-hour counting and specific gravity measurements, and the data in Figure 3 were used to determine the amp-hour capacity for different charge rates. The battery voltages were temperature compensated.

Results of Testing

The results of the testing are shown in Figure 4. Battery volts per cell are plotted against battery SOC for four different "C" rates. ("C" rate is a common form of expression for charge/discharge rates used in the battery literature; a C/1 rate is the total amp-hours of the battery discharged over 1 hour.)

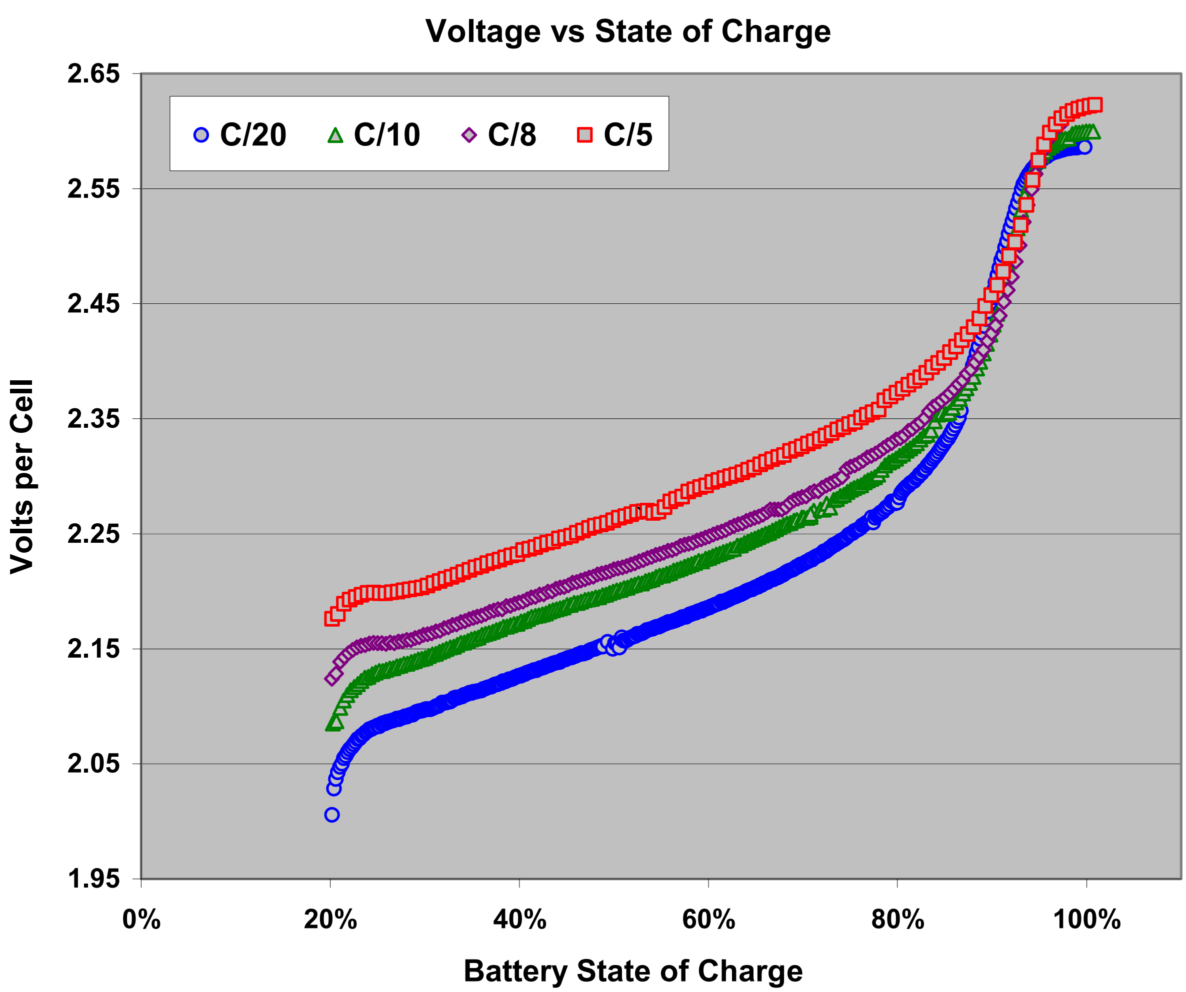

Figure 4. Voltage versus SOC for Different Charge Rates

The graph shows a number of interesting points about battery charging. At SOCs above about 85%, all the charge rates approach the same steep voltage change. This is because at these high SOCs the Coulombic charging efficiency is very poor. The system is mostly producing heat and hydrogen by off-gassing, and the internal resistance of the batteries is about the same regardless of the charge rate or the charge rate history (i.e., it doesn't depend on what happened previously in the charging profile). This is an important point: Charging from 85%-100% SOC is grossly inefficient and should only be done when maintaining the batteries as required per manufacturer's recommendations. (To prevent sulphation and electrolyte stratification, battery manufacturers require periodic boost or equalization charges.) For small wind battery charging systems not undergoing a boost or equalization charge, the battery charging range should be from about 40%-80% SOC.

As shown in the graph, higher charge rates result in higher voltages. This is important because for systems with lower battery/wind capacity ratios, the charge rates will be higher and the voltage of the DC bus will be higher. This can result in charge regulation occurring before the battery bank is charged to its target capacity (about 80%). Figure 5 shows the same test data, but also plotted is a typical charge regulation set point of 2.25 volts per cell. It is important to remember that the data in Figure 5 is for a new battery bank, old battery banks will have a higher internal resistance resulting in a steeper voltage rise.

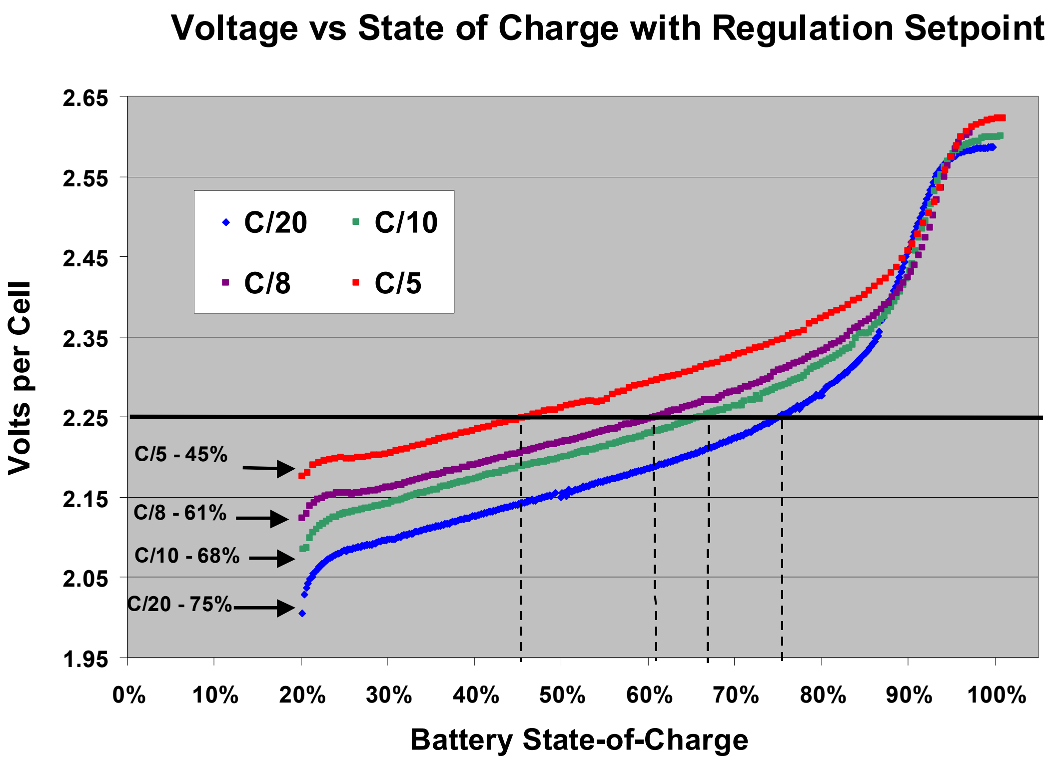

Figure 5. Voltage Versus State-of-Charge for Different Charge Rates

At a C/5 charge rate, the system would go into charge regulation at a battery SOC of 45%, and the wind turbine's power output would be limited. For systems with a battery/wind capacity in the 3-10 range, the batteries would not be charged to more than about a 68% SOC, and much of the excess power would be "dumped." This is because the battery grid is not "stiff" enough, and at the charge rates typical of small wind systems, the voltage rises too fast on the DC bus, and the charge controller limits current by 1) unloading the turbine by reducing current to the DC bus, or 2) shunting the power to a dump load.

Example of Reduced Energy Capture

Reduced energy capture from premature voltage rise due to low battery/wind capacity ratios is very common in small wind battery charging projects in the field. Figure 6 shows the power curve from a system in Isla Tac, Chile, with two 7.5-kW wind turbines. The actual power output from the wind turbine is below the manufacturer's power curve, not because there is anything wrong with the wind turbine, but because the DC bus voltage rises too fast causing the charge controller to regulate power.

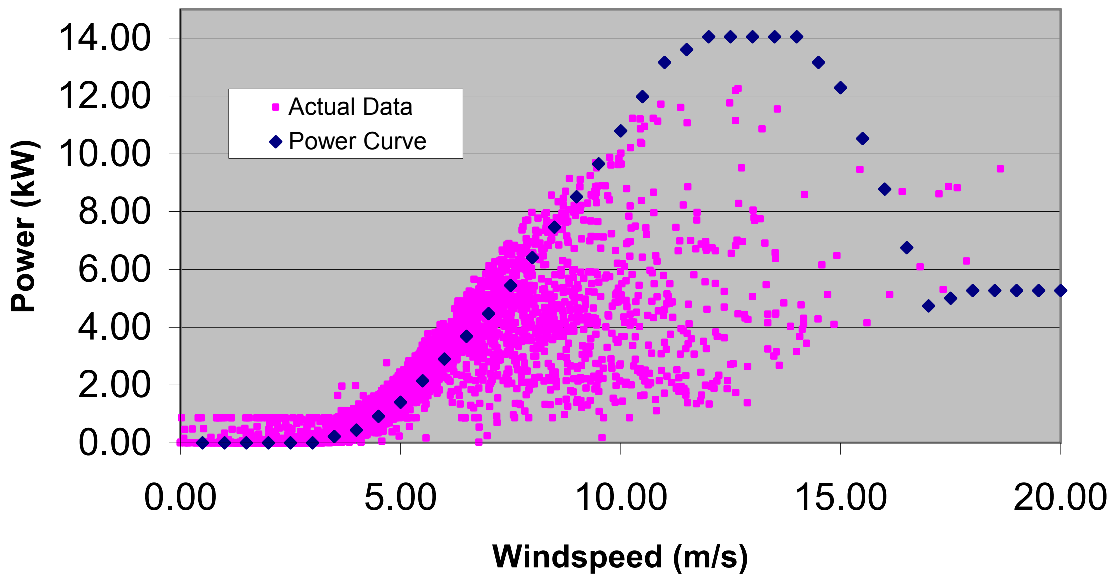

Figure 6. Isla Tac, Chile Array Power Curve and Actual Data for Two Bergey XL-R Turbines

Figure 7 shows a comparison of the actual energy and expected energy from this same system. The manufacturer's power curve is multiplied by the actual wind speed distribution to give the expected energy output. This shortfall in energy output cannot currently be estimated with any existing models or methodologies.

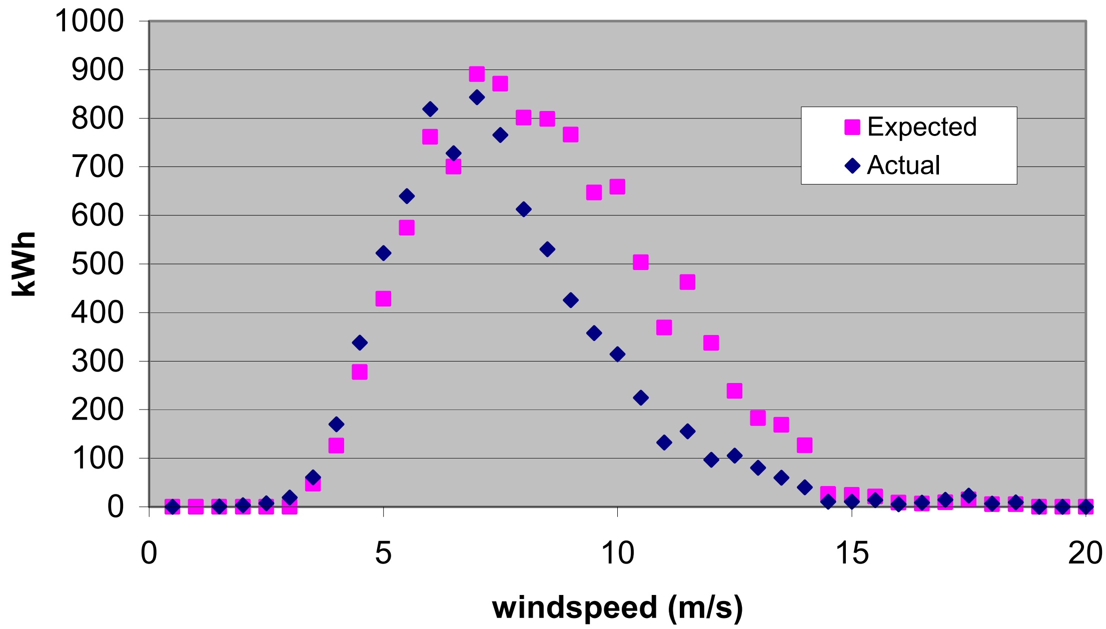

Figure 7. Comparison of Actual & Expected kWh in Isla Tac, Chile

What Can Be Done

The most obvious answer to mitigate the problem of reduced power output from small wind turbine battery charging systems is to increase the battery/wind capacity ratio. This will reduce the voltage rise on the DC bus for a given charge rate and keep the system from going into regulation too soon. However, larger battery/wind capacity ratios will result in higher battery costs. Furthermore, these systems should be modeled to ensure that for a given wind regime and expected wind turbine power output, the system will not be operating predominantly in the inefficient charge regime of 85%-100% battery SOC.

A potentially inexpensive and effective solution to the problem is to implement "smart" charge control algorithms in which battery charge regulation set points are a function of charge rates. For many existing charge controllers, this would be an easy software change. A lookup table could be implemented in the software, and the higher charge rates would allow charge regulation to occur at a higher voltage. However, because the charge controller is protecting the batteries by limiting the current to them, any changes should be thoroughly understood to prevent battery overcharging and potential battery safety problems that could result. Performance models should be updated to model the voltage rise on the DC bus so that charge controller parameters can be implemented without having to under go rigorous battery testing for each battery type.

Certain projects can benefit from having a deferrable load, such as water pumping or heating, and could switch in the deferrable load at higher states of charge so as not to dump the energy. However, this requires custom controls and is very project specific and for most projects deferrable loads don't exist.

Finally, current performance models cannot give adequate estimates of annual energy production from small wind turbine battery charging systems, so these models should be updated to better predict energy capture.he life-cycle-cost tradeoffs between larger battery banks and increased energy capture should be modeled.

Acknowledgments

References

Baring-Gould, I., Newcomb, C., Corbus, D., and Kalidas, R. (2001). "Field Performance of Hybrid Power Systems." Windpower 2001, Washington, DC. June 4-7, 2001.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2002	Conference Paper

4. TITLE AND SUBTITLE

Battery Voltage Stability Effects on Small Wind Turbine Energy Capture: Preprint

5. FUNDING NUMBERS

WER2.1740

6. AUTHOR(S)

D. Corbus, C. Newcomb, E.I. Baring-Gould, and S. Friedly

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER

NREL/CP-500-32511

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Previous papers on small wind turbines have shown that the ratio of battery capacity to wind capacity (known as battery-wind capacity ratio) for small wind systems with battery storage has an important effect on wind turbine energy output. Data analysis from pilot project performance monitoring has revealed shortcomings in wind turbine energy output up to 75% of expected due to the effect of a "weak" battery grid. This paper presents an analysis of empirical test results of small wind battery systems, showing the relationships among wind turbine charging rate, battery capacity, battery internal resistance, and the change in battery voltage. By understanding these relationships, small wind systems can be designed so as to minimize "dumped" or unused energy from small wind turbines.

14. SUBJECT TERMS
wind energy; wind turbines; battery voltage stability; wind turbine energy capture; battery-wind capacity ratio

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102